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IOT-BASED DISTRIBUTED SIMULATION OF INDUSTRIAL AUTOMATION PRODUCTION LINE MANAGEMENT

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Abstract

The IoT maximizes the information and intelligence of large-scale producers, and greatly improves the supervision quality and efficiency of production lines. Existing research fails to use modern logistics simulation for distributed simulation, verification and analysis of industrial automated production line management (IAPLM). Thus, this paper studies the distributed simulation of IoT-based IAPLM. The time domain, component information and other elements are introduced into the distributed Petri network model to realize the optimization of the logic model of the industrial automation production line. The key points of distributed simulation design of IAPLM are introduced in detail, and the timing design of the production process, the mapping of logical model to distributed simulation platform, the structured processing of models, and the construction of simulation strategies for production equipment control are completed. Experimental results verify the effectiveness of the proposed model.

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Key Words: IoT, Industrial Automated Production, Production Line Management (PLM), Distributed Emulation

1. INTRODUCTION

From the phased characteristics of new technology development, verification and application, IoT is still in the primary stage, and its structure and application scenario innovation are still developing and enriching [1-4]. Recently, many industries started to combine the IoT for developing intelligence and automation, aiming to realize the information exchange and interaction between people and people, and between people and things anywhere, anytime, making the management of industrial production and daily life more humanized and refined, and ultimately reaching the ideal state of intelligence [5-9]. In particular, in the field of industrial automation production, the IoT boasts a good prospect. It has replaced the traditional manual statistics, changed the traditional supervision, and realized the safe and reliable supervision of modern production lines [10-22].

Due to the explosive demand for and growth of industrial IoT, many standards and protocols have been defined and applied. Lee et al. [23] proposes a heterogeneous IoT integration for manufacturing. Delgado-Clavero et al. [24] introduces an IIOT data management platform, which promotes the semantics of monitoring industrial IoT devices. Chernorutsky et al. [25] constructed and proved an abstract network set theory model of multi-stage process developing over time. Rúbio et al. [26] describes the latest technologies related to IoT devices and network physical systems, and introduces application cases related to predictive maintenance. Ahmad et al. [27] focuses on the analysis of key failures that affect production activities and their related interactions. In order to improve the fault detection process more accurately and effectively, a conceptual model of intelligent factory data analysis using network physical system and industrial IoT was proposed.

Domestic and foreign research on the IoT-based IAPLM is not thorough enough and lacks detailed analysis. In addition, no distributed simulation, verification and analysis on the IAPLM

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has been carried out with modern logistics simulation. Therefore, this paper studies the distributed simulation of the IoT-based IAPLM.

2. MODEL CONSTRUCTION AND OPTIMIZATION

Because the production tasks of the industrial automation production line system based on the IoT are carried out concurrently, the volume of real-time production data generated is huge. This makes the construction and implementation of distributed simulation model extremely difficult. Therefore, it is necessary to formalize the distributed simulation model scientifically. Petri net is a graphical modelling tool for the production management system with its functions of graphical representation. Compared with the traditional program design block diagram, it can describe the relationship between production tasks, handle production events with concurrency, coordination and competitiveness, and reduce the probability of illogical phenomena in the production management process. The entire industrial automation production line has various production processes and complex flows. There are coordination, configuration and control problems among production processes, production equipment and production materials. To solve this problem, this paper introduces a distributed Petri net model for the time nodes of production task execution and production material configuration information, which optimizes the simulation performance of the model.

Based on the composition of the industrial automation production line, it is described as $X = (P_x, E, H, P_t, N, D, L)$, representing the "time-logic" production process hierarchy of different production equipment in the virtual industrial automation production line system. In model X, the beat is represented by E, the grouping information by H, different production material models by P_x, the time nodes of production equipment for different production processes by P_t, and the structural characteristics of the industrial automation production line by D, the information of different production processes executed by the production equipment by N, and other information included in different production processes conducted by the industrial automation production line by L.

From the above analysis, it can be seen that the following conditions need to be met for different production processes of the industrial automation production line: In the distributed simulation environment, in order to achieve the coordination and control of different production processes, it is necessary to set global time variables; The built distributed simulation model needs to include the necessary production material models and their grouping information of all production processes; The configuration requirements and importance of different production material models in the model need to be preset; The production status of each production equipment is different by default when it executes different production operations; Timely reset the time and space location information of the production process after the end of a production cycle; Different production process management modes and production material allocation rules of production equipment should be consistent with the production process of the actual production line.

The basic Petri net model is represented by $SQ = (R, P, G)$. In order to describe the actual process and logic of the virtual industrial automation production line, time, parts information and other elements are introduced into the SQ model to form the Petri net model of the industrial automation production line. It is supposed that the production resource status set in the system is represented by R, the production resource consumption, change, generation and other operations by PS, the weights of the production operations to occur in the future production status by L, the production status completed by different production equipment by R_x, the change process of production equipment or production resource status in the production process by G, the change amount in the production equipment time domain by N, and the change amount of production equipment i by N_i, the transformation amount in a single time domain of the production equipment by n_j, the initial coordinate point of the production equipment by (a_{jr}, b_{jr}, c_{jr}), and the initial Euler angle of the production equipment by $(\beta_{jr}, \gamma_{jr}, \alpha_{jr})$, the target coordinate point of the production equipment by (a_{jo}, b_{jo}, c_{jo}), and the target Euler angle of the production equipment by $(\beta_{jo}, \gamma_{jo}, \alpha_{jo})$. If the initial information of the model is represented by N_0 and the time node by P_T, then there is a model:

$$IAP\text{-}SQ = (R, R_x, PS, G, L, N, N_0, P_t, P) \tag{1}$$

$$N = \{N_i\}\ (i = 1, \ldots, m),\ \ N_j = \{n_j\}\ (j = 1, \ldots, l) \tag{2}$$

$$n_j = \{a_{jr}, b_{jr}, c_{jr}, \beta_{jr}, \gamma_{jr}, \alpha_{jr}, a_{jo}, b_{jo}, c_{jo}, \beta_{jo}, \gamma_{jo}, \alpha_{jo}\} \tag{3}$$

The number of cycles is gradually increased, and the “time-logic” production processes of the production equipment is stacked until the preset value is reached, meeting $P_T = \{p_t\}$, $p_t \in [0, P]$. It is supposed that the time domain of production equipment i is represented by P_i, and the production process time domain of production equipment is represented by P, meeting $P=[P_i]$, $(i = 1, \ldots, m)$. Assuming that a certain time domain of a production equipment is represented by p_j, a certain production process of a production equipment can be divided into multiple time periods, namely $P_j = \{p_j\}$, $(j = 1, \ldots, l)$. $P_j = \{p_{jr}, p_{jo}\}$ represents the start and end nodes of the production process replacement time of the production equipment.

IAP-SQ structure diagram can be obtained according to the principle and structural characteristics of the production line, which describes the working state and flow of the main line of the whole set of power switch cabinet. S_0 to S_{12} are the production status of the complete set of power switch cabinets. The empty status is represented by R_0, the assembly completion by R_1, the assembly completion of the switch cabinet shell by R_2, and the finished products after all the assembly processes are completed by R_{12}. The production line is divided into 12 basic processes. The completed state of the front work required for the production of the complete set of power switch cabinet is represented by Rx_0 to Rx_{12}. For example, the current transformer assembly is represented by Rx_0, and the voltage transformer assembly by Rx_{12}. The process of assembly of production materials and parts for complete set of power switch cabinet for different production processes is indicated by PS_1 to PS_{12}. The assembly times of parts are represented by L_1 to L_{12}.

Before the completion of the assembly of the circuit breaker and fuse, it is necessary to cooperate with the circuit breaker and fuse. The cooperation process is described by building parts and components to cooperate with Petri net $IAP\text{-}SQ = (R, R_x, G, L, N, N_0, P_t, P)$. The assembly completion of different production materials in the coordination process is represented by UH_i $(i = 1, \ldots, m)$. The configuration process of production materials is represented by $PT_{2i\text{-}1}$, and is combined by the configuration of production materials. The combination of the first i production materials is represented by Re_i. The combination operation of the first i production materials is transferred to the next production material configuration process, which is represented by $PT_0, PT_2, PT_4, \ldots, PT_{2i}$. The final combined parts are represented by Rx_i, which is also the R_x in the *IAP-SQ* network.

All the production processes such as production material configuration have independent production processes. Petri net $HIAP\text{-}SQ = (T, Pf, G, Q, N_0, P_t, P)$ is used to configure the configuration of a single production material model.

Assuming that the equipment status is represented by T_1 to T_i, the reset process of automatic stacking equipment or mechanical arm after the completion of production material configuration is represented by Pf_{-1} to Pf_{-i}, and the process of driving production operation is represented by Pf_1 to Pf_i. The operation finally achieves the completion of production material configuration, that is, the HP_i status in *UIAP-SQ*. Fig. 1 shows the *UIAP-SQ* model structure diagram. Fig. 2 shows the *HIAP-SQ* model structure diagram.

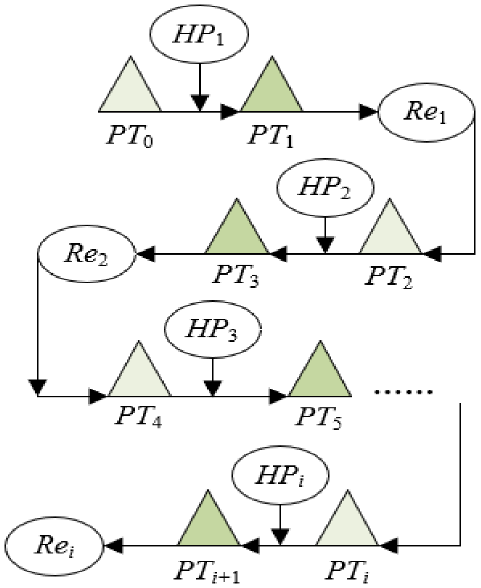

Figure 1: Structure chart of UIAP-SQ model.

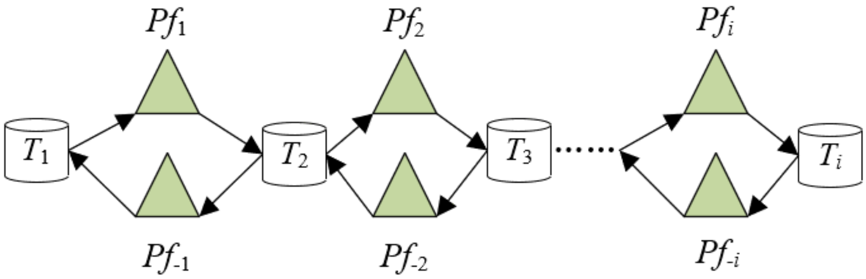

Figure 2: Structure chart of *HIAP-SQ* model.

To accurately describe the behaviour logic relationship of the entire industrial automation production line in a distributed way, this paper constructs a nested Petri net model group based on the *IAP-SQ*, *UIAP-SQ* and *HIAP-SQ*. The industrial automation production line completes the configuration through the mechanical arm, so the logic and time rhythm of the mechanical arm for different production processes should be consistent with the characterization of the *HIAP-SQ* model in the Petri network.

After the construction of nested Petri net model group is completed, the logic of the construction process of the distributed simulation model for the management of the entire industrial automation production line will be more rigorous and clearer. In addition, the built distributed simulation model needs to be combined with the actual production environment to realize the mapping of different production equipment from the real production environment to the distributed simulation model, and complete the real-time operation, maintenance and monitoring of the industrial automation production line.

3. DISTRIBUTED SIMULATION

3.1 Production process timing design

The production interval of two adjacent products is defined as the beat. The production modules of the industrial automation production line are arranged according to the process sequence, that is, the production equipment participating in the production is subject to one-way action between processes according to a unified rhythm. The information collection of the distributed simulation model for the IoT-based industrial automation production line system is relatively convenient, and the simulation of different production processes can be driven by the timing information. Therefore, it is particularly important to design the time beat of the production process reasonably for the smooth implementation of the simulation. Fig. 3 shows the production process timing design flow chart. Because the production process in the actual industrial automation production line is usually continuous, this paper defaults that the production process of the same working procedure is the same, and the time beat of different working procedure is also the same. It is supposed that the minimum production rhythm of a single production material in the simulation process is P_x, that is, the simulation model completes the production process of the production material in the $[0, P_x]$ time interval, and the linkage effect of the production process can be achieved by maintaining the periodicity of the production operation. Due to the sequential relationship and certain consistency of production processes, the execution time of each production process is decomposed into two parts: equipment execution time and waiting time. Assuming that the execution time of the production process is P_x, the production time of large parts assembled by multiple small production materials can be expressed by $l P_x$, where l is the number of sub-production processes of small and medium-sized production materials of large parts.

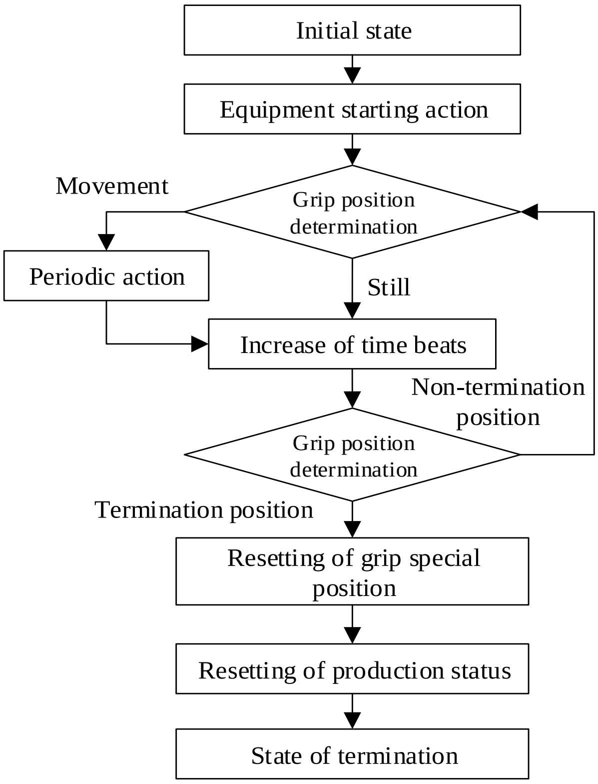

Figure 3: Timing design flow of production process.

The working process of the automatic palletizing equipment or mechanical arm can be regarded as a complete production process in the entire industrial automatic production line, that is, the total working time of the equipment from the start of the production task to the initial working point can be regarded as P_x. Therefore, it is necessary to arrange the production process design and motion trajectory planning of the manipulator on the basis of full consideration of P_x constraints. In the design of industrial automation production line, many factors need to be considered in the selection of P_x, especially the two parameters of total production process quantity and production material quantity of the production line and the running time limit of the distributed simulation model. The whole simulation process of IAPLM can be seen as a distributed simulation process of a production system with multiple production procedures connected in turn and small production procedures partially circulating. By default, the initial state of the new production process in the production system is consistent with the termination state of the previous production process. The distributed simulation of the industrial automation production line of the complete power switch cabinet can be realized by simulating different production procedures in the research time domain in sequence.

3.2 Mapping of logical models to distributed simulation platforms

The production status and operation in the nested Petri net model group correspond to the entity production equipment in *Unity3D* distributed simulation. The grouping and hierarchical relationship between *IAP-SQ*, *UIAP-SQ* and *HIAP-SQ* models are determined, and behaviour driving compilation of automatic stacking equipment or mechanical arm are carried out according to the production processes. The framework of the model group is built through programming to realize the multi beat cycle and dynamic switching of the production processes of the production line. The action speed of all processes is completely flexible and controllable. The realization of distributed simulation of industrial automation production line is based on the mapping of model group to simulation platform. Fig. 4 shows the running framework of the distributed simulation model. The simulation framework consists of federation member module, IAPLM simulation problem solver module, simulation system module and network service system module.

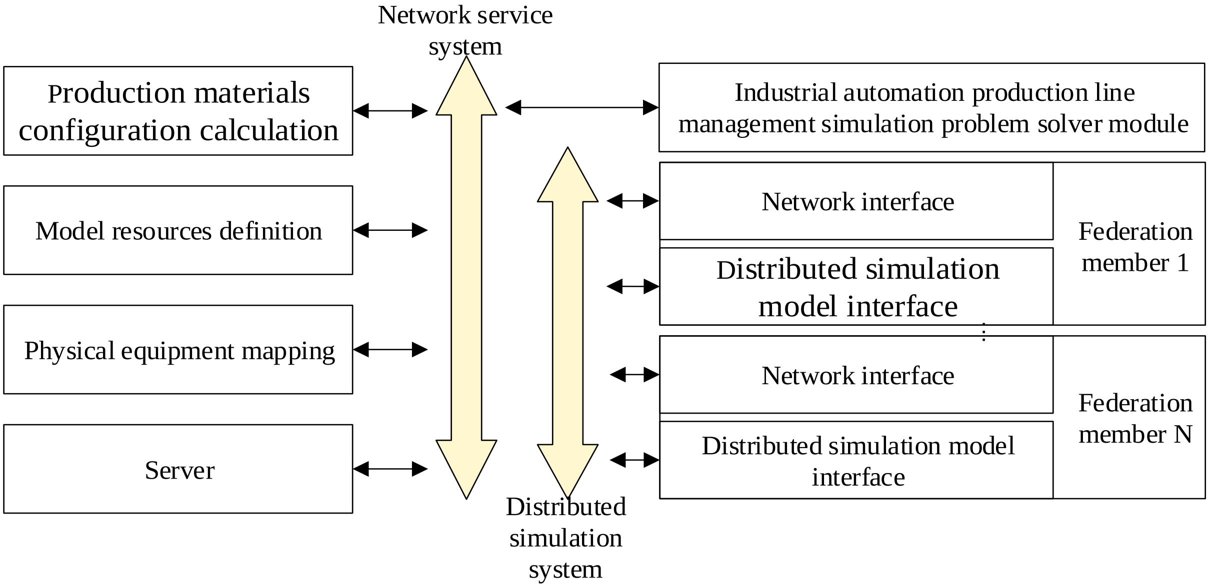

Figure 4: Distributed simulation model running framework.

3.3 Model structuring processing

In the mapping process from model group to *Unity3D* simulation platform, the production equipment is first structured, and the production equipment with the same production procedures can be linked into groups. Each small production material in the group has a hierarchical relationship with the whole large part, which meets the rule of “the upper part moves while the lower production materials move, and the lower production materials move while the upper part do not move”. Based on this rule, all production materials on the production line can be constructed in hierarchy view of *Unity3D* simulation platform. *Control.cs* script is created for the production body of the industrial automation production line, and all large and small variables are defined in C#.

Definition of production procedures:

Public Transform production process-circulation; // Define the linkage of the production procedures

Definition of production equipment and materials:

Public Transform robot; // definition of mechanical arms

*Public Transform productionproces*01; // define the production equipment of production procedures 01

Linkage hierarchy relationship:

Production process-circulation =product Object. transform. Get Suppart (1). *transform*; // the sub-production material of the industrial automation production line corresponding to the linkage process of the production procedure

robot=product Object. transform. Get Suppart (2).*transform*; // the sub-production material of the industrial automation production line corresponding to the production process of the mechanical arms

*productionprocess*01-*productionprocess-circulation.transform. Get Suppart*(1).*transform*; // the sub-production material of the industrial automation production line corresponding to the production equipment of the production procedure 01

…………

3.4 Simulation strategy

During the mapping model groups to *Unity3D* simulation platform, it is important to map the production operations in the nested Petri net model groups that meet the rhythm design constraints. The mechanical arm can use *transform*, *Translate* and *transform. RotateAround* function respectively to grasp production materials for translation and rotation. For example, when the relative movement distance of production material 01 on axis *a* is 0.257 meters, the following coding can be performed:

Product Object. Find ("*component*01"*). transform.*
Translate (*new Vector*1 (0.257,0,0)),

Because the corresponding position of the centre point of the main axis is the *a* axis of *Virtuallocationt*01, within the time interval of [0.75*P*, 0.85*P*], the automatic palletizing equipment and mechanical arm will rotate 40 degrees around the *a* axis every time they grasp. The time interval *P* is divided into 100 segments, and 4 degrees are rotated in each segment from Section 75 to Section 85. It can be achieved using the following code:

If ((*timepoint* >75) & (*timepoint*<85))
this. transform. RotateAround (*productObject. Find*("*Virtuallocationt*01"). *transform. position*, *Vector*1.*up*,4),

4. EXPERIMENTAL RESULTS AND ANALYSIS

The information collection of distributed simulation models for industrial automation production line systems is generated based on the IoT. Fig. 5 shows the simulation efficiency of the model under different sample numbers and minimum production beat lengths. The figure shows that the smaller the minimum production rhythm is, the more scientific the configuration scheme of the manufacturing resources will be in the process of distributed simulation. The production resources at different positions cannot be fully applied and allocated until the sequence of the production procedures and the implementation sequence and time consistency of different production procedures are fully considered, so as to meet the demand of distributed simulation of industrial automation production line.

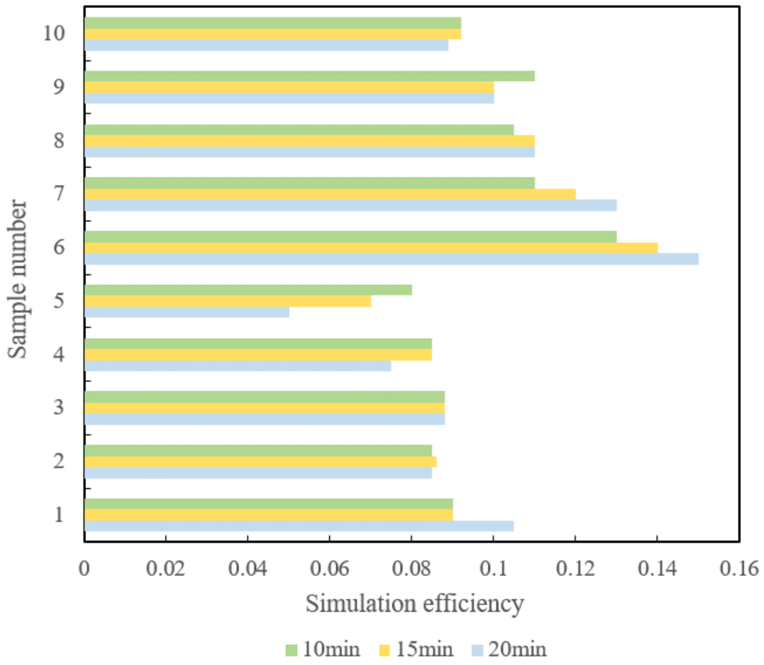

Figure 5: Simulation efficiency of the model under different minimum production beats.

To make the simulation more reliable, a comparative experiment was conducted on three models: CrossGrid (reference model 1), NEESGrid (reference model 2) and HLAGrid (reference model 3). Table I shows the experimental data under different production tasks. Fig. 6 gives the curvilinear display of the experimental results. Our model fully considers the expected execution time of production tasks on production equipment, and keeps all production equipment in working state. The optimal management strategy selected is better than the simulation results of CrossGrid, NEESGrid and HLAGrid models.

Table I: Experimental data from different models.

Reference model 1	No. of task	22	36	48	51	69	114	165	217
	Time of completion	136	147	169	235	208	236	328	311
Reference model 2	No. of task	26	31	49	56	62	114	162	225
	Time of completion	101	152	136	120	139	147	109	261
Reference model 3	No. of task	24	38	46	51	63	104	192	214
	Time of completion	137	169	152	134	185	120	269	274
Model in this paper	No. of task	29	33	48	56	69	141	162	242
	Time of completion	96	125	131	147	105	136	185	269

The utilization rate of production equipment of industrial automation production line is shown in Fig. 7. The optimization results of our model are basically consistent with the calculation results in the actual production by the traditional management mode. Figs. 8 and 9 respectively compare the production material demand and product inventory under different management modes. The IAPLM optimization results obtained by our model can achieve lower product inventory and higher production material demand, which further verifies the effectiveness of our model.

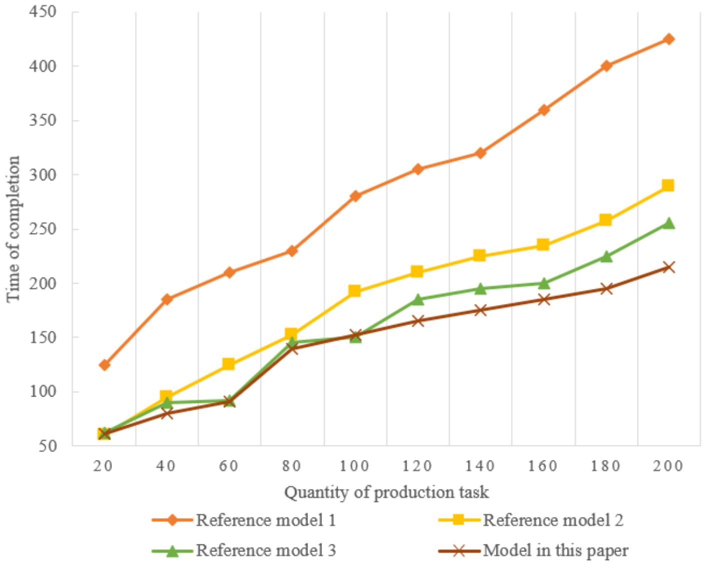

Figure 6: Comparison of experimental results of different models.

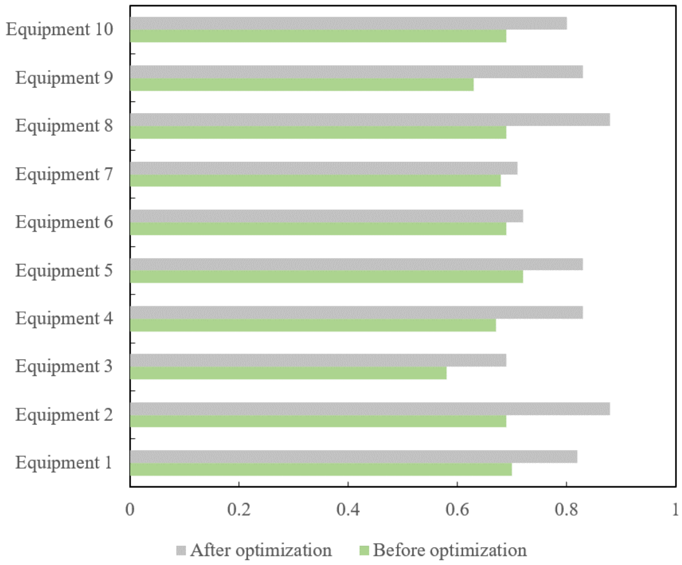

Figure 7: Comparison before and after utilization of production equipment.

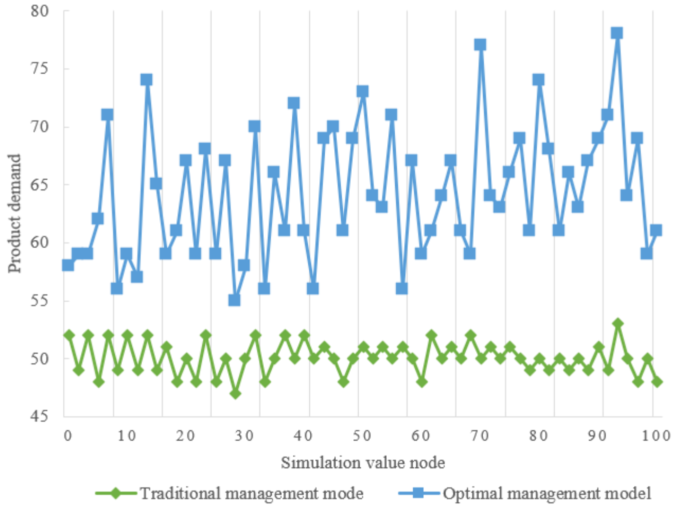

Figure 8: Comparison of production materials demand under different management modes.

Figure 9: Product inventory comparison under different management modes.

5. CONCLUSION

This paper studies the IoT-based distributed simulation of IAPLM. The time domain, parts information and other elements are introduced into the distributed Petri net model to optimize the logic model of industrial automation production line. The key points of distributed simulation design of IAPLM are introduced in detail, and the production process timing design, the mapping of logic model to distributed simulation platform, the structure processing of model and the construction of simulation strategy for production equipment management and control are completed. The simulation efficiency of our model was tested under different minimum production beats, and a comparative experiment was conducted on CrossGrid, NEESGrid and HLAGrid. The results verify that the optimal management strategy of our model is superior to the simulation results of the three comparative models. The effectiveness of our model is further validated by comparing the production material demand and product inventory under different management modes.

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